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SUMMARY

A flight-test investigation has been conducted in connection with the development of a lunar landing simulator to provide some preliminary information concerning the handling qualities of a tethered manned lunar-landing vehicle operating in a simulated lunar gravitational field. Proportional-type controls were used; no artificial stabilization was used during this investigation; and the results of the investigation are based entirely on pilots' opinions. The piloting task was visual hovering. The effect of a lunar gravitational field was considered to be well represented by the servocontrol system employed to maintain five-sixth of the weight of the vehicle and pilot. The arrangement of the pilot's controls was good and the control sensitivity was harmonious. Under these conditions the vehicle could be maneuvered fairly easily with reaction-jet controls, and the control power required in pitch, roll, and yaw was found to be somewhat higher than that required by helicopters and by the AGARD requirements for VTOL aircraft. Larger pitch and bank angles were required for linear acceleration of the vehicle than for acceleration of helicopters and VTOL airplanes, but for the small maneuvers used in these tests this large ratio of angle to acceleration was not particularly bothersome to the pilot. Height control of the vehicle with a vertical-acceleration capability of only 0.06g and no vertical-velocity damping was considered to be unsatisfactory for normal operation.

INTRODUCTION

In the development of a lunar landing simulator at the NASA Langley Research Center, a simplified mockup of the suspension system and flight vehicle were built and tested to check some of the ideas and systems to be incorporated in the full-scale simulator. In the process of performing this work some preliminary information on the handling qualities of a manned lunar landing vehicle operating in a simulated lunar gravitational field was obtained; the present report presents the preliminary results of these handling qualities. The test vehicle was a lightweight open framework which carried the pilot. It was equipped with conventional helicopter-type pilot controls which provided roll, pitch, yaw, and altitude control by means of compressed-air jets. In order to simulate flight in the lunar gravitational field, five-sixths of the weight of the vehicle and of the pilot were supported by an overhead cable which incorporated a servocontrol system for controlling the amount of weight supported, and one-sixth of the weight was supported by a compressed-air jet which also provided height control. The handling qualities of this vehicle in the simulated lunar gravitational field were determined on the basis of the pilots' opinions for various values of control power for the performance of the maneuvers possible in the limited operating area available. All the tests were made without stability augmentation - which might be considered as the manual reversion condition in the case of failure of the stability augmentation system.

Related work on the handling-qualities requirements of lunar landing vehicles is reported in references 1 and 2. Reference 1 presents the results of a fixed-base simulator study, and reference 2 presents the results of some experimental work done with the X-14 jet VTOL airplane in which the airplane was flown along several proposed lunar landing trajectories.

FLIGHT VEHICLE

A drawing and photograph of the vehicle are presented in figures 1 and 2, respectively. The vehicle was constructed of aluminum alloy and had a 3/8-inch plywood platform to which were attached flight-control levers and a seat for the pilot. In order to provide an attachment point for the overhead suspension cable a simple parallelogram suspension system was used. The system had $\pm 10^\circ$ freedom of travel in pitch and roll at the vehicle attachment points and the upper end of the parallelogram had $\pm 10^\circ$ of freedom in roll and 180° of freedom in yaw. (See fig. 1.) The air-supply hoses gave some restraint to the yawing motions of the vehicle since they were attached to the ends of the crossbar which yawed with the vehicle. This restraint was measured as 0.18 ft-lb/deg of yaw with the hoses pressurized as in flight. There was no corresponding restraint of the hoses on the pitching and rolling motions as long as the vehicle motions stayed within the $\pm 10^\circ$ of freedom allowed by the pivots in the parallelogram suspension system since the pivots were below the point at which the hoses were attached to the vehicle.

The vehicle had a main thrust (lifting) jet directly beneath its center of gravity and had reaction-control jets fore and aft of and to the sides of its main body as indicated in figure 1. Compressed air for the main lifting jet and for the reaction-jet controls was provided by flexible air hoses which fed into a small plenum chamber located directly below the center of gravity of the vehicle and attached to the bottom of the plywood platform. The thrust valve for controlling the thrust of the main lift jet was attached to the plenum chamber and air was furnished to the reaction-control valves from the plenum chamber by three flexible air hoses. For all practical purposes the vehicle had zero damping in pitch, roll, and climb; however, there was a small amount of damping in yaw due to the air hoses. (See figs. 2 and 3.)

The pilot controls on the vehicle were similar to those of a helicopter. (See fig. 1.) The control system was entirely manual, and no artificial stabilization was provided. Pitch and roll control were applied with a control stick between the pilot's legs, yaw control was applied with conventional rudder pedals, and thrust was controlled with a lever operated by the pilot's left hand (similar to the collective pitch lever of a helicopter). The control stick had ± 6.8 inches of fore-and-aft travel for pitch control and ± 7.6 inches of sideways travel for roll control. The stick was mechanically connected to nonbleed proportional type valves which had two exhaust ports. The exhaust ports for the pitch control valve were connected at the front and rear of the vehicle by flexible hoses to short lengths of metal tubing which exhausted downward and acted as reaction-control nozzles. The roll valve was connected in a similar manner to reaction jets located on each side of the vehicle. When a control was applied in either pitch or roll, one exhaust port on the valve opened and provided compressed air to one of the control nozzles to provide a pitching or rolling moment in the desired direction proportional to the control stick deflection. The input to the vertical motion due to a pitch or roll control was considered to be negligible and did not present any problems to the pilots when the controls were applied. The rudder pedals were pivoted near the heel of the pilot's foot and had a travel of $\pm 18^{\circ}$ which corresponded to a linear motion of about ± 2 inches of the ball of the foot. The pedals were mechanically connected to a valve of the same type as the pitch- and roll-control valves. But, since the yaw-control jets were located below the center of gravity of the vehicle, the yaw-control jets were connected in pairs in such a manner that a couple was produced when yaw control was applied, and thus eliminated any induced pitching moments. To accomplish this effect, each line leading off of the two yaw valve exhaust ports had a "tee" inserted in the line and then the two lines leading off the tee were directed to opposite sides of the vehicle and one line connected to a reaction jet facing forward while the opposite line connected to a reaction jet facing rearward. The control effectiveness, or the control moment produced by a given stick or pedal deflection, could be changed as a ground adjustable feature by changing the distance of the individual control jets from the center of gravity of the vehicle.

The vehicle weighed 175 pounds and the pilot weighed 185 pounds for a total weight of 360 pounds. The moments of inertia including the pilot were about:

Pitch, slug-ft^2	16.5
Roll, slug-ft^2	13.2
Yaw, slug-ft^2	27.1

This value of yawing moment of inertia includes the moment of inertia of the part of the air-supply hoses that swung with the vehicle as it rotated in yaw and was actually measured by swinging the vehicle in yaw on the flight-test setup with the hoses attached and pressurized to the pressure used in flight.

TEST EQUIPMENT AND SETUP

A sketch illustrating the test setup is shown in figure 3. The vehicle was suspended from an overhead cable attached to a hydraulically driven servo-controlled winch which allowed vertical freedom of movement. This servocontrol system maintained a constant tension in the cable equal to five-sixths of the combined weight of the vehicle and pilot and thus simulated the moon's gravitational pull which is one-sixth of that of the earth. A detailed description of this cable control system is given in the appendix. Support for the remaining one-sixth of the weight plus the additional force required for vertical maneuvers was provided by the downwardly directed jet controlled by the pilot. It was considered important that the supporting cable remain vertical as the vehicle translated horizontally in order to minimize any pendulum restraint effects of the cable on the motions of the vehicle. The system used to keep the cable vertical at all times is shown in figure 3. In this system the vehicle support cable went through a ring 50 feet above the floor, and this ring could be moved horizontally anywhere in a 10-foot square by cables moved by air-driven winches. These winches were controlled by operators to move the ring in the traverse cables to keep the vehicle support cable vertical as the vehicle moved around in the test area. This traverse system allowed the pilot to fly the vehicle in a pattern approximating a 10-foot square without appreciable extraneous cable effects.

The air for the main thrust jet and attitude control jets was supplied through flexible plastic hoses which were suspended from the ceiling of the test area and attached to a crossbar on the suspension cable above the sensor for the servocontrol system. The test setup was operated in one of the return passages of the Langley full-scale tunnel, which gave a test area about 50 feet long and 50 feet wide with a 65-foot-high ceiling. The effects of recirculation of the exhaust air from the compressed-air jets was negligible, mainly because of the large size of the test area, and also because all flights were made at least 6 feet or higher above the floor of the test area.

TESTS

For all tests the vehicle was hung from the suspension cable, the servocontrol system was turned on in an open-loop mode to assume six-sixths or all of the weight, the manual brake was released on the cable drum (see fig. 3), the pilot then applied just enough thrust for hovering flight, and then the servocontrol system was switched to a five-sixth of the weight regulating system. If the pilot wished to maneuver the vehicle, he would apply the proper thrust or attitude control, the operators of the two winches of the cable traversing system shown in figure 3 would observe the motion of the suspension cable and apply control to the traversing system in order to keep the suspension cable vertical. The normal duration of a particular flight was about 3 minutes. To terminate a flight, the manual brake was applied to the cable drum, the servocontrol system was switched off, and the pilot cut the main air jet.

The flight investigation was conducted in two parts. The first part was conducted before the cable traversing system was installed. These tests consisted mainly of an evaluation of the height control because of the restraint of the support cable on the other motions of the vehicle. The second part of the investigation was conducted with the cable-traversing system installed and operating and consisted of an evaluation of the roll, yaw, and pitch controls for both steady hovering flight and for the limited translational maneuvers possible within the 10-foot-square maneuver area.

The results of the investigation are based entirely on the pilots' opinions of the controllability of the vehicle. Two research pilots participated in the investigation, both of whom had extensive experience in propeller and jet aircraft and in helicopter and VTOL research aircraft.

A few static-force tests were made to determine the thrust available for the reaction-jet controls. These tests were made with the hovering thrust jet producing 55 pounds of thrust to simulate hovering flight, and the results are presented in figure 4. From the static-force test results and the moments of inertia of the vehicle, it was possible to calculate the angular accelerations in pitch, roll, and yaw presented in table I.

RESULTS AND DISCUSSION

General Comments

The piloting task has a very important effect on the results of the investigation; therefore, it should be clearly understood what the piloting task was. In the present tests, the pilot performed three tasks, all of which would normally be classified as part of the general visual hovering task. These tasks were: (1) to maintain steady hovering flight, (2) to restore the vehicle to steady hovering flight after disturbances, and (3) to perform deliberate translational maneuvers (both horizontal and vertical) within the limits permitted by the test setup.

Before proceeding with the results of the flight investigation, a few of the pilots' comments concerning the flight vehicle should be presented. The pilots considered that the flight control system used as such to fly the lunar vehicle was satisfactory and, in general, the arrangement of the pilot's controls was good and the control sensitivity was harmonious. In some preliminary flight tests, it was found that the control system had an excessive dead spot and excessive control friction. The control system was consequently reworked to minimize these factors. It was not possible to eliminate completely the dead spot in the air valve used for controlling the flow to the control jets, but it was reduced to the values shown in figure 4; and these values were considered to be acceptable by the pilots on the basis of their flight tests of the vehicle. The actual values of stick and pedal forces and control system friction were not measured, but it was apparent that every attempt must be made to keep any friction in the control system to a minimum, particularly in pitch, roll, and height control. The friction in the control system was considered to be of an acceptable level by the pilots after the system had been reworked. The pilots felt that the gimbal travel between the parallelogram support system and vehicle was too restrictive ($\pm 10^{\circ}$ travel) and should have been larger to allow greater pitch and roll angles for greater translational accelerations.

With a vehicle as small as that of the present investigation, the motion of the pilot relative to the machine can have an important effect on the motions of the vehicle. Consequently, to prevent movements of the pilot insofar as possible, the seat was provided with a back which wrapped well around the side of the pilot's body, and the pilot was strapped in tightly with a shoulder harness.

Height Control

The pilots felt that the effect of a lunar gravitational field was probably well represented by the servocontrol electronics system employed to maintain five-sixth of the weight of the vehicle since they could not detect any effects of the hydraulic system such as lag or overshoot even when thrust control was changed rapidly. The vehicle had only enough excess thrust available to produce an upward acceleration of 2.0 ft/sec^2, or about 0.06g, as measured from figure 5 which shows a time history of the rate of climb following an abrupt application of full thrust. The maximum downward acceleration capability with the thrust shut off completely was, of course, 1/6 g. The thrust control available was found by the pilot to be adequate for smooth steady hovering flight, but was considered to be too weak to be satisfactory for effecting rapid changes in height and for checking modest rates of descent. It also was inadequate for maintaining height precisely during rapid translational maneuvers when the vehicle had to be tilted to appreciable angles. The overall pilot opinion rating assigned to the height control, as shown in test 1 of table I was 4, by using the Cooper pilot opinion rating system described in table II. This result is in general agreement with the results of references 3 and 4, which also indicate that the height control was unsatisfactory for the case of this low value of height control power where there was no vertical-velocity damping.

Pitch, Roll, and Yaw Control

The pilot was very conscious of the larger bank angles required to start or stop linear translational motions in the simulated lunar gravitational field in comparison with the bank angles of jet VTOL aircraft in the earth's gravitational field; however, for the small maneuvers used in these tests this larger ratio of angle to acceleration was not particularly bothersome. These larger bank angles are the result of the fact that the thrust required to support a given mass is only one-sixth as great in the lunar gravitational environment as in an earth gravitational environment, and that this smaller thrust must be tilted about six times as far to produce a given translational acceleration of the mass. In general, it was not very difficult to fly the vehicle in translation with the traversing system employed. In fact, when maneuvers were made slowly and steadily, the cable translation system was good. When rapid translational motions were made, however, the pilots could feel the manual translation system tending to lag or overshoot. When the cable translating system was not operating at all, the support cable was found to have very large effects on the pitching and rolling characteristics of the vehicle. First, if the pilot was simply attempting to hover steadily, directly beneath the cable attachment point, the restoring forces provided by the cable as a result of translational motions had a definite stabilizing effect and made the vehicle much easier to fly. And second, if the pilot attempted to make translational maneuvers, he found that he was seriously hampered by the cable restraint and the motions that he could perform were very limited and were greatly affected by the cable. The cable translation system was therefore considered an essential part of the system for evaluation of the pitch and roll control.

The results of the investigation of the pitch, roll, and yaw control are shown in table I with the Cooper rating scale described in table II. With the maximum available control moments for all controls (pitch, roll, and yaw) (see table I, test 2), it was possible to fly the vehicle fairly well while executing maneuvers. For this flight condition the calculated angular accelerations in pitch, roll, and yaw were 0.79, 0.65, and 1.13 rad/sec^2/inch of stick or pedal travel, respectively. With this amount of control the pilot considered the pitch control as almost optimum and assigned a rating of 1.5, and he considered the roll and yaw control as marginally satisfactory and assigned a rating of 3.5.

As the control power was reduced, the factor that became most apparent was the increased time it took to translate over a given distance and stop. One reason for this increase in time was that the reduced control effectiveness required a longer time to pitch or bank the vehicle to develop a translational acceleration, and it also required a longer time to pitch or roll the vehicle to stop the acceleration once it was started. A second reason was that the pilot tended to worry about overshoot when executing maneuvers with the reduced control effectiveness and tended to be very cautious in the use of control. The minimum control power (see table I, test 3) that the pilots considered marginally satisfactory for flying the vehicle produced angular accelerations in pitch, roll, and yaw of 0.54, 0.65, and 1.13 rad/sec^2/inch of stick or pedal deflection, respectively. With this amount of control effectiveness, the pilot was able to fly spiral maneuvers with both vertical and horizontal translation without too much difficulty and to execute these maneuvers with some degree of precision. When the control moments were reduced in test 4 to about 50 percent of the values required to give the marginally acceptable ratings of test 3, the vehicle could be flown smoothly and easily for steady hovering flight, but the control of the vehicle was not satisfactory if the pilot attempted rapid maneuvers in translation. As the control moments were further reduced in test 5 to about 25 percent of the values required to give the marginally acceptable ratings of test 3, the control of the vehicle became almost unacceptable for even mild translational maneuvers.

The vehicle had unusually large stick travels available, but in analyzing the movies taken during the investigation, it was noted that in no case did the pilot use more than one-half the available travel in any normal steady flying or maneuvering. The only time he ever exceeded one-half the available travel was when he used maximum deflection in pulse inputs to see how much control was available and this was done only for the two lowest control power conditions. For the yaw control the pedal travel was relatively small (±2 inches) and the pilot frequently used the maximum deflection available when trying to yaw the vehicle rapidly. This experience indicates that the amount of total control power required is that which would provide an acceleration of about 1.8 rad/sec^2 in pitch, 2.3 rad/sec^2 in roll, and more than 1.9 rad/sec^2 in yaw.

INTERPRETATION OF RESULTS

Two questions naturally arise regarding the interpretation of the results of the present tests. One question is how to scale the results to account for differences in vehicle size; and the other question is how the present results compare with helicopter and VTOL airplane experience.

A scaling factor is included in both helicopter and V/STOL airplane requirements such as those of reference 5 which specify the control power required as a function of $1/(W + 1000)^{1/3}$. This size factor has been proven to be fairly accurate for helicopters from about 2,500 to 30,000 pounds but has never been checked for vehicles nearly as small as the present research vehicle (360 pounds). The following table shows a comparison of the control power required for satisfactory behavior in the present tests with the requirements of reference 5 for a 360-pound vehicle. The control power required by the V/STOL aircraft requirements was calculated by using the weight of the vehicle in the earth gravitational field since weight is used in the requirements as an indication of the geometric size of the aircraft and since the requirements were set up in terms of earth weight as the indication of size.

	AGARD V/STOL requirements (ref. 5)	Present research vehicle
Control sensitivity for pitch, rad/sec^2/in. . . .	0.26	0.54
Control sensitivity for roll, rad/sec^2/in. . . .	0.40	0.65
Total control for pitch, rad/sec^2	1.04	1.8
Total control for roll, rad/sec^2	1.20	2.3
Total control for yaw, rad/sec^2	1.05	1.9

It should be noted that the yaw control was not compared on the basis of sensitivity in the table because it was found that the pilot frequently hit the stops on the rudder pedals and it is believed, on the basis of past experience, that when this condition occurs, the pilot's rating is more influenced by the total control power available than by the sensitivity at smaller control deflection.

The data in the foregoing table indicate that the present research vehicle required from 60 to 100 percent more control than is indicated as being required by the AGARD V/STOL requirements. It seemed possible that this lack of agreement might have resulted from the fact that the size scaling factor might not be exactly applicable at the very small size of the present vehicle since it has never been checked in this size range. Consequently, another comparison was made using unpublished results of flight tests of a very small helicopter (500 pounds gross weight) for direct comparison with the results obtained with the present research vehicle. The results of this comparison are shown in figure 6. The comparison must be made on the basis of less than satisfactory control sensitivity in pitch and roll since the control sensitivity of the helicopter was somewhat weak and was not varied. The yaw control of the present vehicle and the small helicopter could not be compared since the helicopter had far too much yaw control for satisfactory behavior, and the present vehicle was not tested in this range of control sensitivity.

The comparison presented in figure 6 shows that the present research vehicle required 25 percent more control sensitivity in pitch and 75 percent more control sensitivity in roll than the small helicopter to obtain the same pilot ratings. This result is in general agreement with the previous comparison of the present results with the V/STOL requirements of reference 5 which showed that the present vehicle required 60 to 100 percent more control than was indicated by the requirements. Pilot ratings are not a very exact quantity for close comparison, but the results of both of these comparisons seemed to indicate that the present jet-powered vehicle operating in a simulated lunar gravitational environment did require somewhat more control power than is required by helicopters and the requirements of reference 5 for V/STOL aircraft.

COMPARISON WITH RELATED STUDIES

It should be noted that in the lunar-landing simulation conducted with the X-14 jet VTOL airplane, and reported in reference 2, it was concluded that the control power required for the simulated lunar landings was only 20 percent of that which had been found to be necessary for normal hovering flight as a VTOL airplane. The difference between that result and the results of the present investigation seems to be one of difference in piloting task. In the investigation of reference 2 the pilot made an approach directly to the landing site and landed there without any last-minute maneuvering to select an exact spot for touchdown. In the present investigation the task was the same as that of a VTOL aircraft in hovering which in effect assumes that the pilot may not know whether he wants to land on a given spot until he gets there, and that he may then want to move quickly to a more suitable nearby spot.

The results of the present investigation are in agreement with the results of the fixed-base simulator study of reference 1 for the lowest value of control sensitivity used in the present tests where the results of both investigations showed pilot ratings of about 6, which is almost completely unsatisfactory. At higher values of control sensitivity, however, the results of the two investigations diverge. The results of reference 1 show that, as the control sensitivity is increased, the handling qualities become worse, evidently because of oversensitivity of the control, and that no pilot ratings better than 6 are obtained at any value of control sensitivity. On the other hand, the results of the present investigation show that, as the control sensitivity was increased from the lowest value, the handling qualities became progressively better until they became satisfactory at the highest values of control sensitivity tested. This trend of improving handling qualities with increasing control sensitivity, shown by the present investigation, is in agreement with the trend of results reported in reference 6. A possible explanation of the discrepancy between the results of the present investigation and those of the fixed-base simulation at the higher control sensitivities is that the pilot of the simulator tended to overcontrol with relatively modest control sensitivities because of an inadequate display of information to the pilot and because of the lack of motion cues resulting from the fixed-base nature of the simulator.

CONCLUDING REMARKS

A brief investigation has been conducted to provide some preliminary information concerning the handling qualities of a manned lunar-landing vehicle operating in a simulated lunar gravitational field. Proportional-type controls were used; no artificial stabilization was used in the investigation; and the results of the investigation are based entirely on pilots' opinions. The piloting task was visual hovering. The effect of a lunar gravitational field was considered to be well represented by the servocontrol system employed to maintain five-sixth of the weight of the vehicle because the pilots could not detect any effects of the hydraulic system such as lag or overshoot even when thrust control was changed rapidly. The arrangement of the pilot's controls was good and the control sensitivity was harmonious. Under these conditions, the vehicle could be maneuvered fairly easily with reaction-jet controls, and the minimum control sensitivities which gave marginal satisfactory controllability were found to be somewhat higher than those required by helicopters and by the AGARD requirements for V/STOL aircraft. As would be expected, larger pitch and bank angles were required for linear acceleration of the vehicle than is the case in the earth's gravitational field with helicopters and VTOL airplanes. For the small maneuvers used in these tests, however, this larger ratio of angle to acceleration was not particularly bothersome to the pilot. Height control of the vehicle, which had a maximum upward acceleration capability of only 0.06g and no vertical-velocity damping, was considered to be unsatisfactory for normal operation.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 5, 1964.

APPENDIX

DESCRIPTION OF VEHICLE SUPPORT CABLE SYSTEM

The object of the vehicle support cable system was to support five-sixth of the weight of the vehicle under the varying input disturbance conditions imposed by motions of the vehicle and the pilot's manipulation of the thrust control. A schematic diagram of the mechanical part of the system is shown in figure 7 and a block diagram of the control system is shown in figure 8. As shown in figure 7, the vehicle was supported by a cable through a strain gage, which served as a sensor; and the cable was payed in or out by a winch driven by a servocontrolled motor to maintain a tension of five-sixth of the vehicle weight, or 300 pounds, in the cable. Because of the varying nature of the input disturbances, a hydraulic motor was chosen to actuate the system since it had the highest torque-to-inertia ratio and the fastest response obtainable in a small package.

In the regulator system a voltage corresponding to 300 pounds of tension on this strain gage was applied to the regulator input as the reference. The servo loop was closed as shown in figure 8. This system, as shown, is a servo-control system with a command input of 300 pounds calling for an output of 300 pounds. This diagram or analysis does not include all the dynamics of the system. Cable-lateral-motion dynamics, the winch-drive dynamics, and the effect of hydraulic compression and line expansion were left out. These frequencies were filtered out of the system. The diagram as shown contains only the motor dynamics plus the cable spring and mass. The system was analyzed and drawn in terms of acceleration. The disturbance inputs were assumed to be pure force.

The equations for the system can be derived in terms of two dynamic loops: the acceleration regulator and the damper. This derivation makes it easier to analyze the effects of each. The closed-loop expression for the acceleration regulator is

By using two integrators $\left(K_1/s \text{ and } K_2/s\right)$,

$$\frac{\text{Output}}{\text{Input}} = \frac{K_1K_2K_4}{s(Ts + 1) + K_1K_2K_4} \tag{A1}$$

By using one integrator $\left(K_1/s\right)$,

$$\frac{\text{Output}}{\text{Input}} = \frac{K_1K_4}{Ts + 1 + K_1K_4} \tag{A2}$$

where the input is the air jet force and the output is the acceleration and

K_1, K_2	integrator gains
K_3	damper amplifier gain
K_4	hydraulic motor gain
K_5	strain-gage gain
s	Laplace operator
T	motor time constant

$T_1 = T + K_3K_4K_5$

It can be seen from a comparison of these two equations that a much faster transit response can be obtained from the quadratic than from the first-order lag.

The closed-loop expression for the damper is

$$\frac{\text{Output}}{\text{Input}} = \frac{K_4 s}{\left(T_1 + K_4\right)s + 1} \tag{A3}$$

The cable-vehicle longitudinal dynamics can be eliminated from the mathematics of this system because of the nature and point of disturbance input. The closed-loop system does not include the dynamics of the cable-vehicle longitudinal motion since the spring is a direct transmitter of the output force of the motor. In this case the motor never has to accelerate the vehicle mass.

This system, as shown, could not be landed on a hard surface. The vehicle could have landed only if upon touchdown the double integrator system was switched open.

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TABLE I.- FLIGHT-CONTROL COMBINATIONS USED IN FLYING LUNAR VEHICLE

[For all tests, acceleration capability upward 0.06g, downward 0.17g]

Test	Control	Radius[a], in.	Acceleration, rad/sec^2/in.	Pilot rating
Height-control tests[b]				
1	Pitch	28.3	0.33	(c)
	Roll	28.3	.40	(c)
	Yaw	22.2	.64	(c)
	Height			4
Pitch-, roll-, and yaw-control tests				
2	Pitch	66.88	0.79	1.5
	Roll	45.38	.65	3.5
	Yaw	39.38	1.13	3.5
3	Pitch	45.38	0.54	3.5
	Roll	45.38	.65	3.5
	Yaw	39.38	1.13	3.5
4	Pitch	26.13	0.31	5
	Roll	19.88	.29	5
	Yaw	19.38	.56	5
5	Pitch	14.38	0.17	6
	Roll	10.63	.15	6
	Yaw	14.63	.42	6

[a]Distance of control jets from vehicle center of gravity.
[b]Cable translational system not operating.
[c]Poor simulation because of restraint of support cable; no rating given.

TABLE II.- PILOT OPINION RATING SYSTEM

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Failure of a stability augmenter.

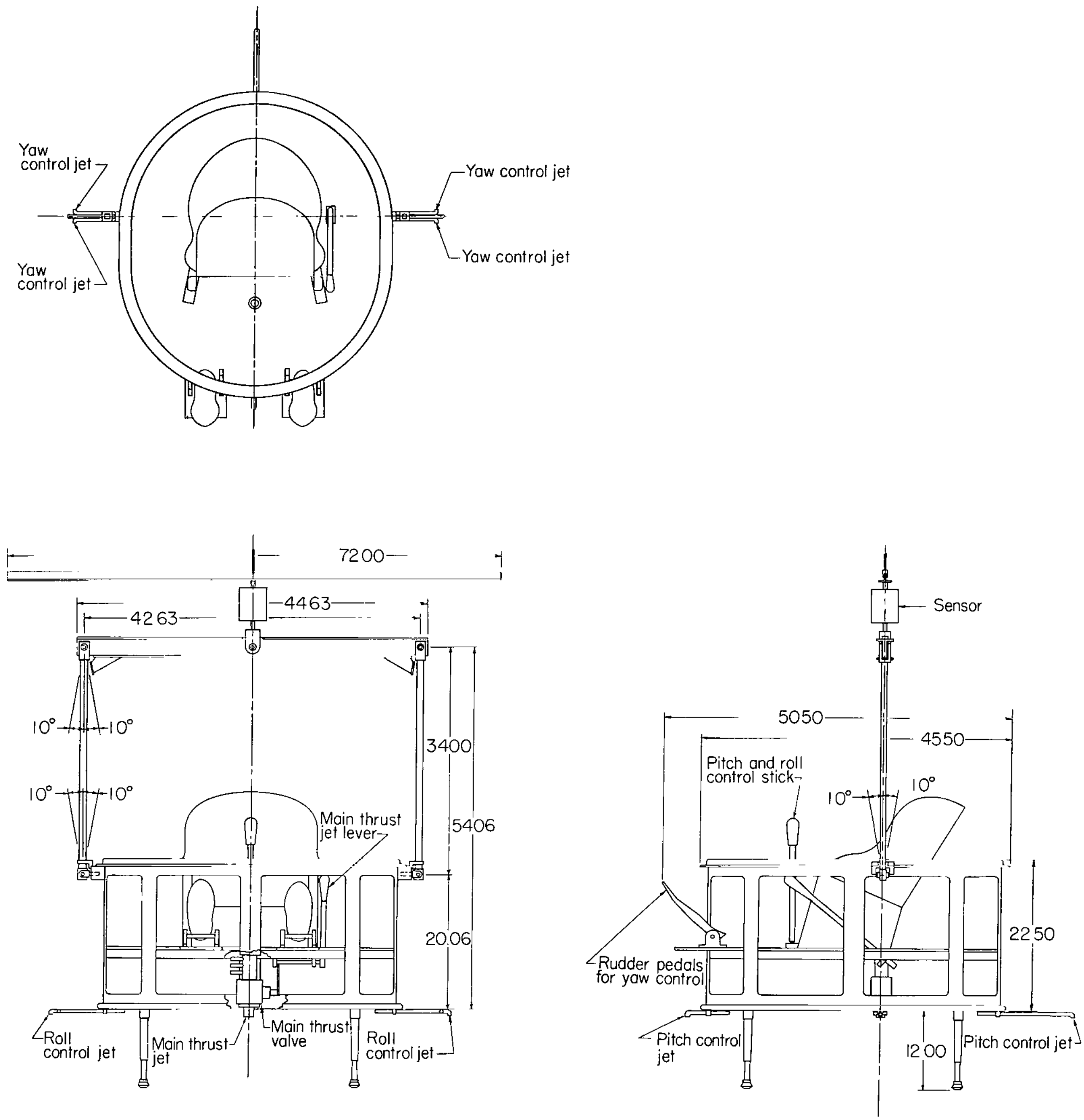


Figure 1.- Three-view drawing of test vehicle. All dimensions are in inches.

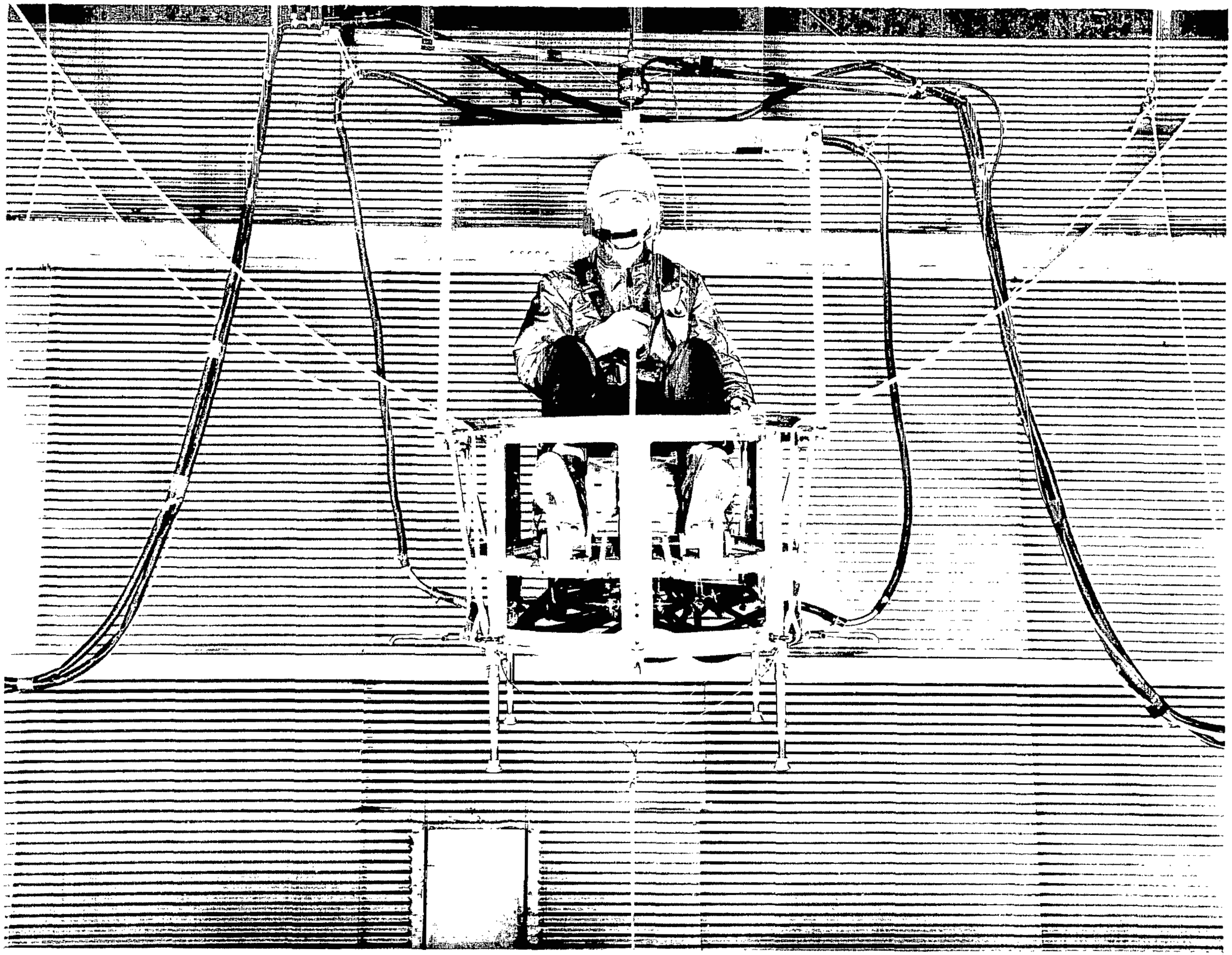


Figure 2.- Photograph of test vehicle. L-62-1458

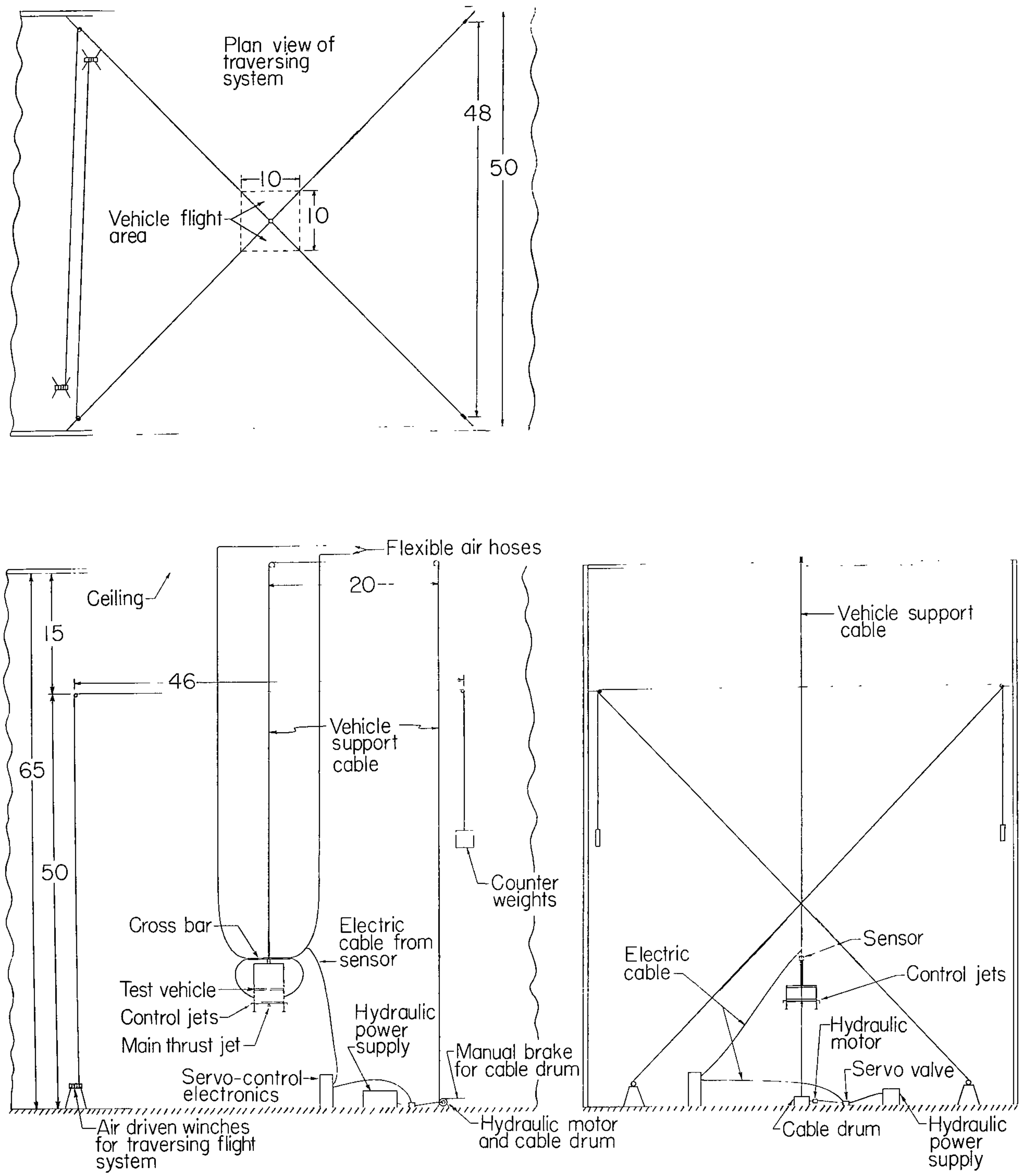
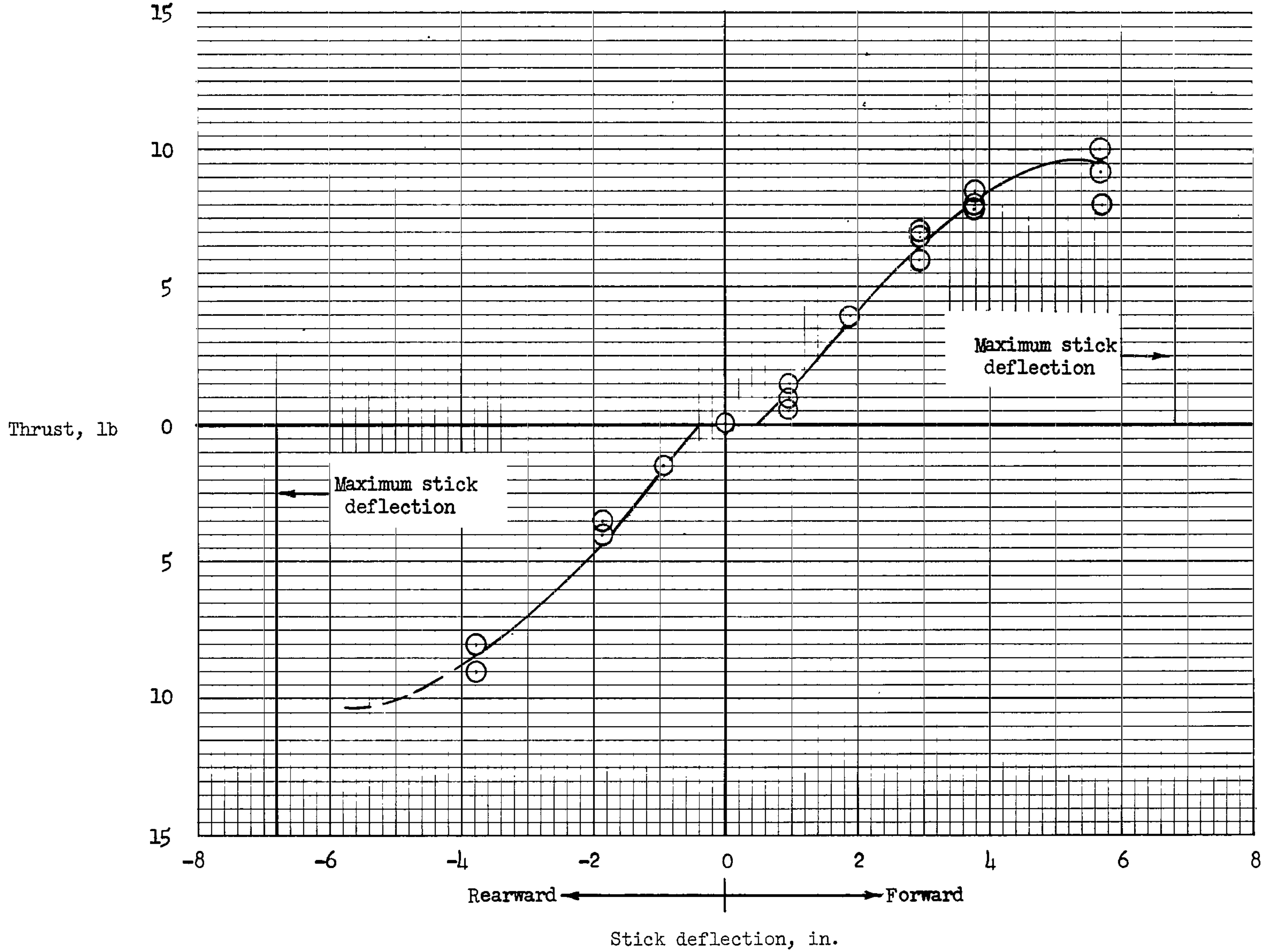
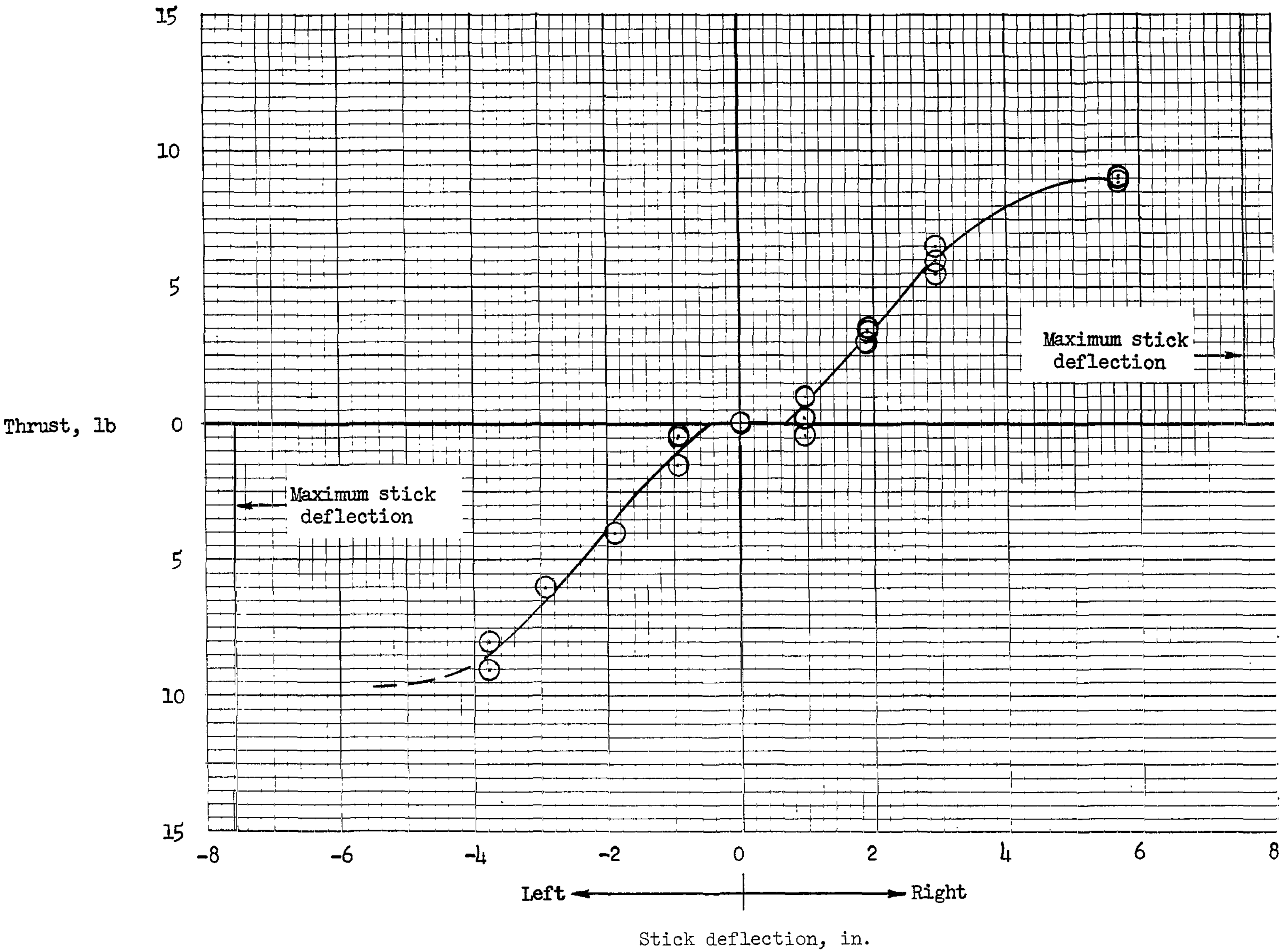


Figure 3.- Sketch of flight-test setup for lunar landing vehicle in return passage of full-scale tunnel. All dimensions are in feet.



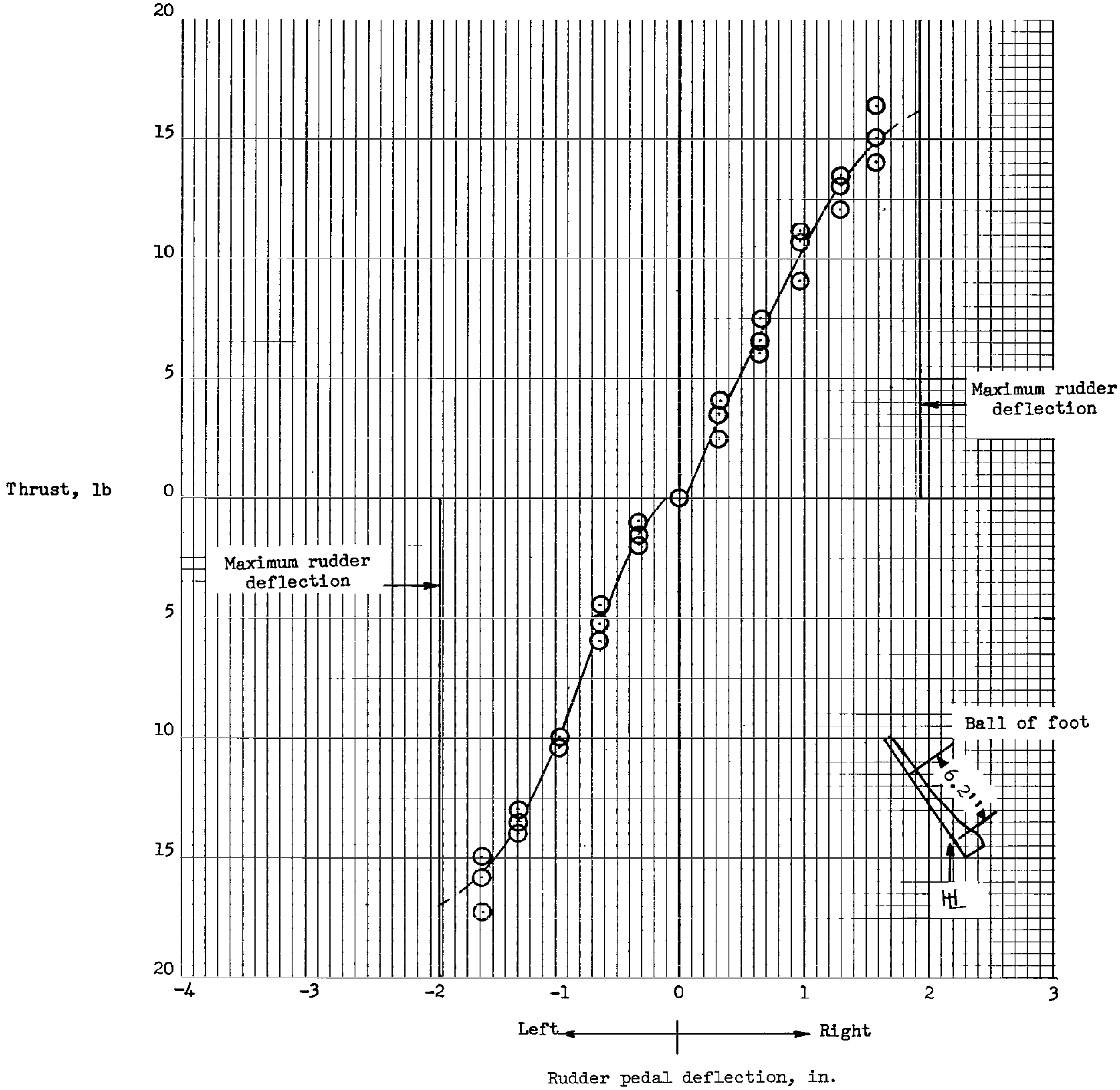
(a) Pitch control.

Figure 4.- Variation of control thrust with control deflection. Main jet thrust, 55 pounds.



(b) Roll control.

Figure 4.- Continued.



(c) Yaw control.

Figure 4.- Concluded.

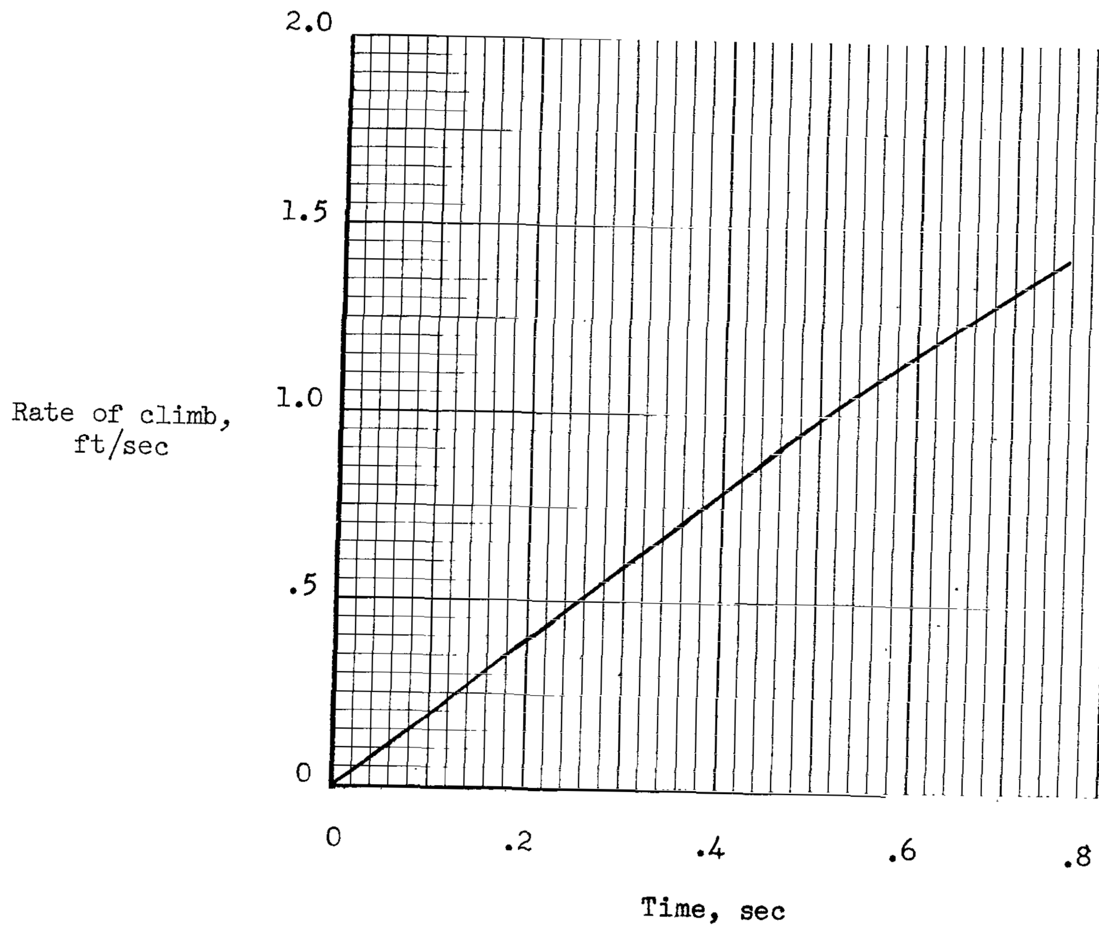


Figure 5.- Variation of rate of climb with time for an abrupt application of maximum thrust.

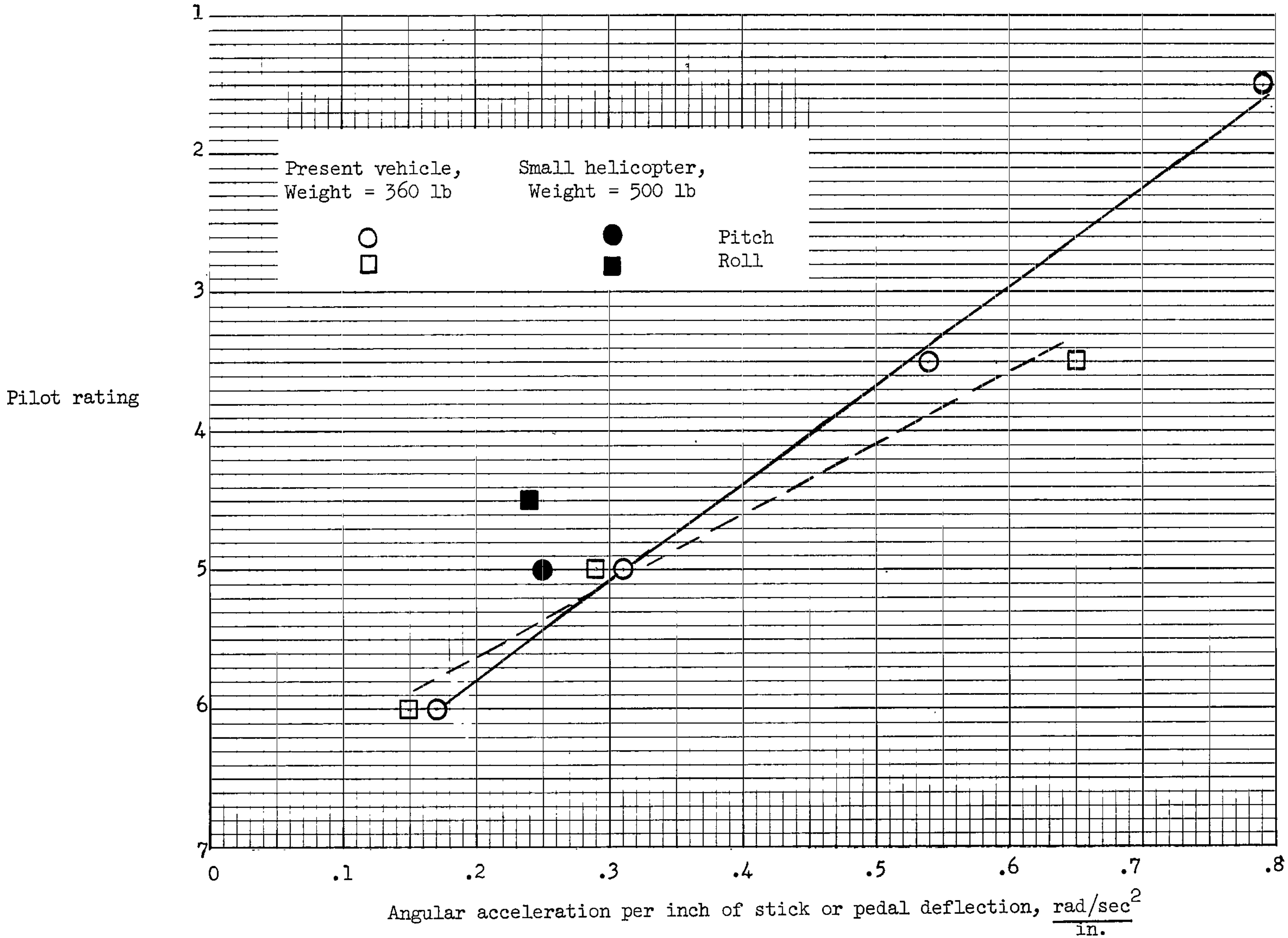


Figure 6.- Comparison of results from the present investigation with those from flight tests of a small helicopter.

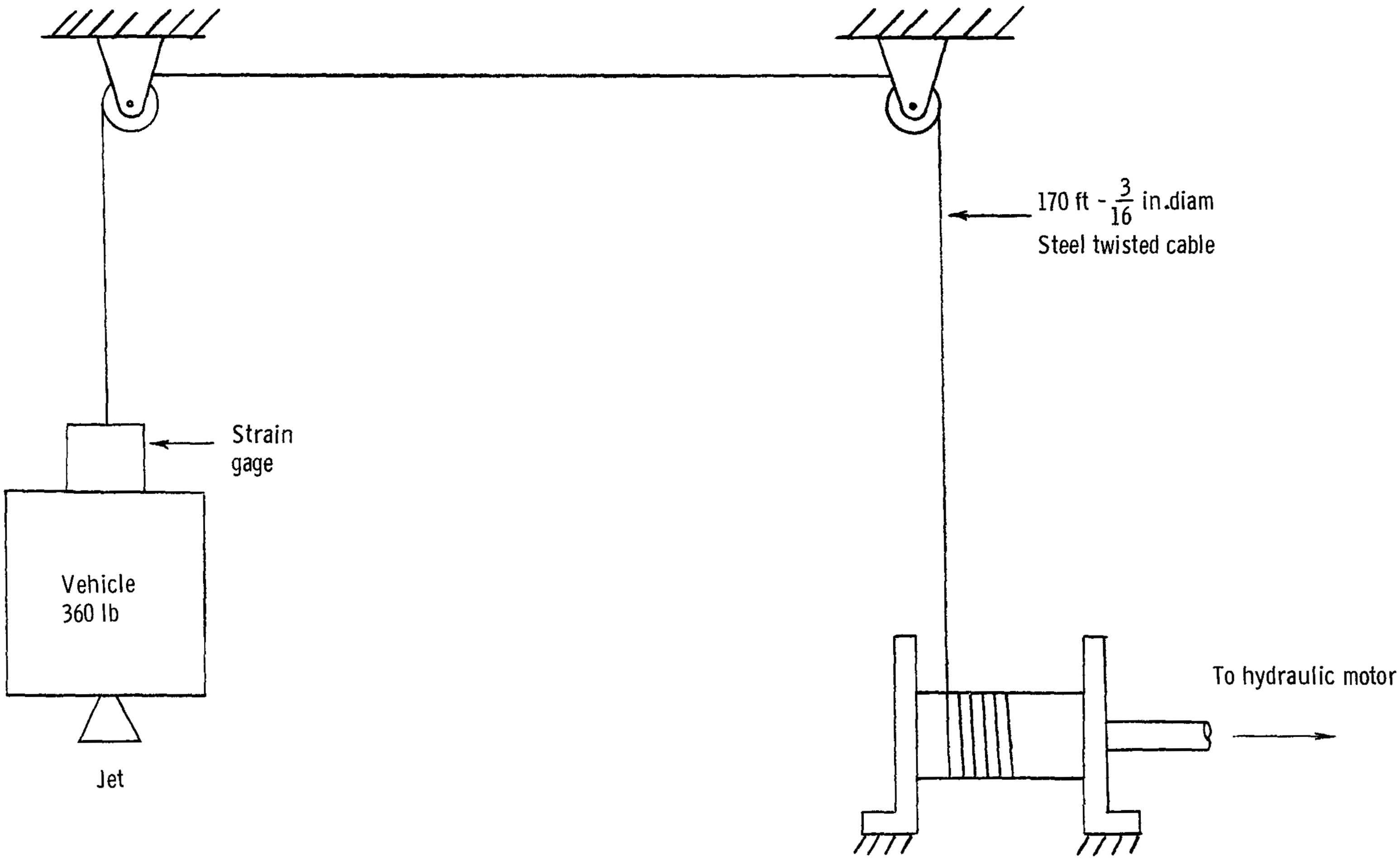


Figure 7.- Schematic of mechanical drive system.

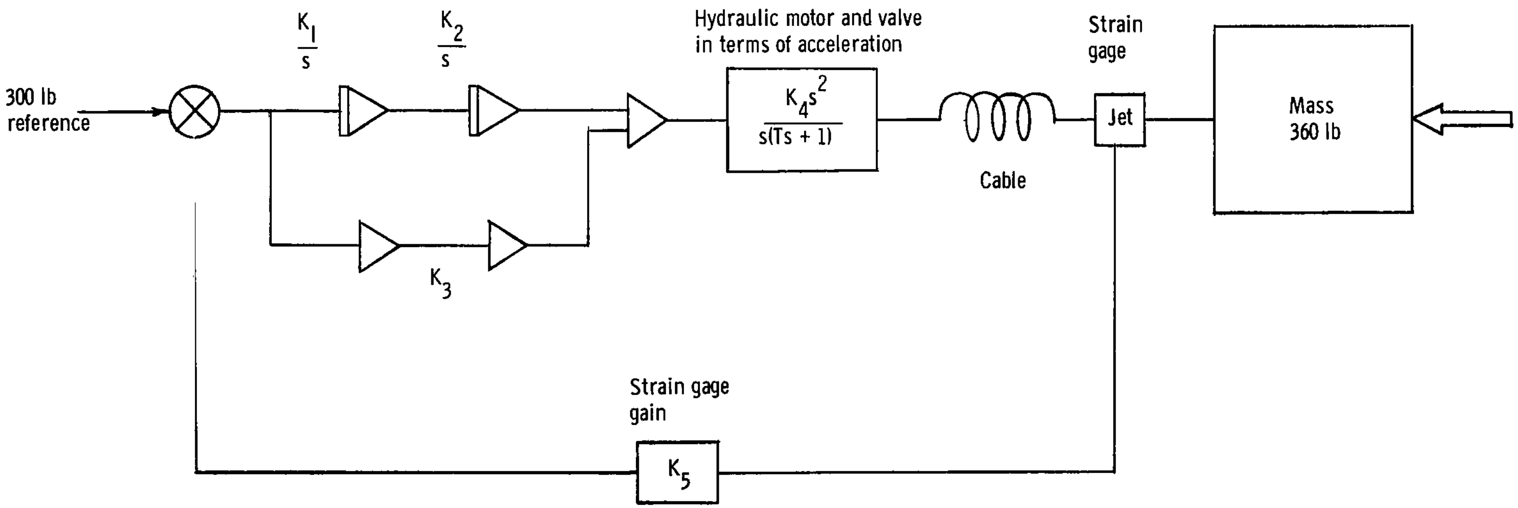


Figure 8.- Block diagram of servocontrol system.

NASA-Langley, 1965 L-4024

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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